X-1 to X-Wings
Developing a Parametric Cost Model

2015 NASA Cost Symposium

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NASA - Armstrong Flight Research Center

Introduction

- In today's cost constrained environment NASA needs an X-Plane data base and parametric cost model that can quickly provide a rough order of magnitude cost predictions for experimental aircraft.

- The model should be based on critical aircraft design parameters, such as weight, size, and speed, as well as some sort of complexity factor..

- It's commonly known among cost engineering professionals, both government and industry that weight based Cost Estimation Relationships (CERs) have the highest correlation.

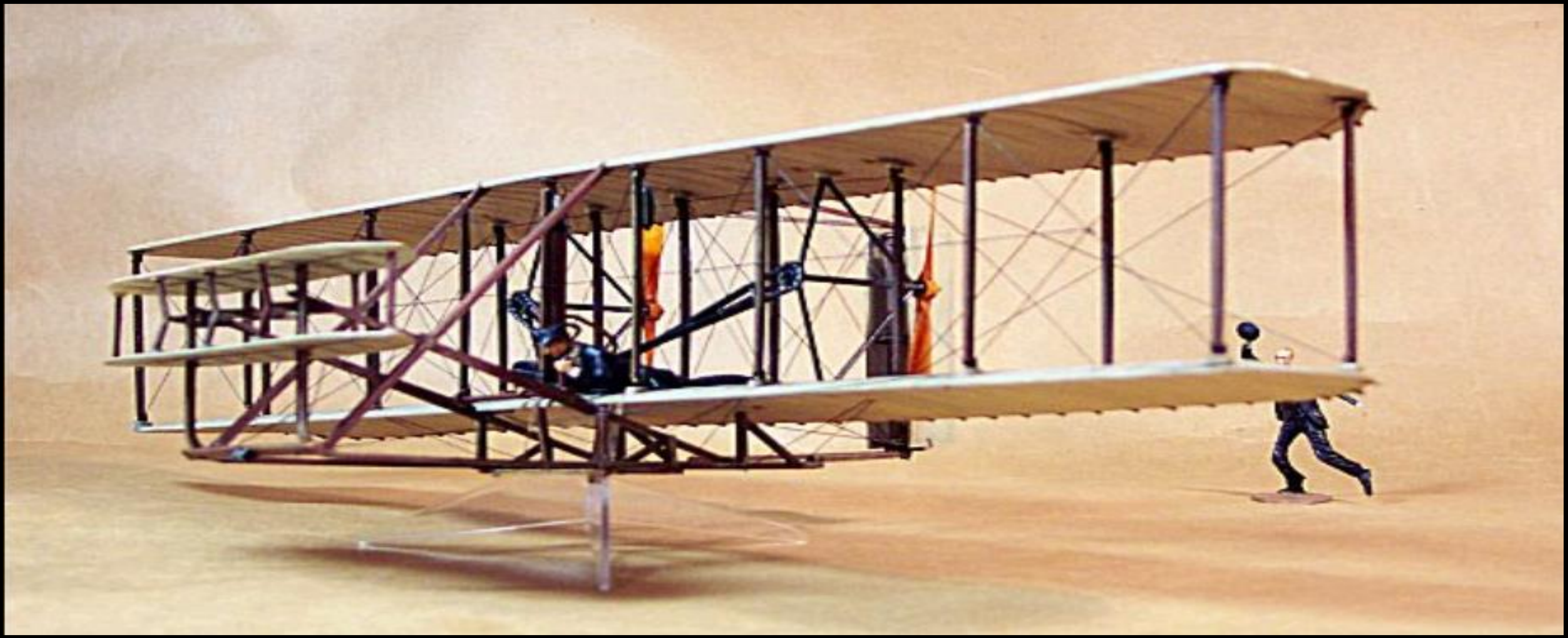
- Last fall 2014 - the authority was given on a non-interference basis to develop an X-Plane Parametric Cost Model.

- Then early spring 2015 – I was given opportunity to hire a Summer Intern (PhD Student) to assist in developing CERs using Regression Analysis.

Definition of an X-Plane

- X-planes (from the 1946 Bell X-1 through the current Lockheed Martin X-56) are a series of experimental United States airplanes and helicopters (and some rockets) used to test and evaluate new technologies and aerodynamic concepts.
- **X-planes are not prototypes, and are not intended or expected to go into full-scale production.**
- **X-planes are flight research tools.**
- X-planes are produced in multiples, typically 2 or 3, to ensure the completion of program objectives.
- The "X-" designation is assigned by DoD and used to indicate the higher risk associated with the dedicated research mission objectives.
- The "X" or experimental designator is a U.S. military aircraft designation like "B" for bomber, "F" for fighter, and "T" for trainer and is assigned to a U.S. research vehicle by the U. S. Department of Defense (DoD)
- Not all US experimental aircraft have been designated as X-planes; some received US Navy designations before 1962, while others have been known only by manufacturers' designations, non-'X'-series designations, or classified codenames.

Challenges in getting cost data



Throughout history every aircraft manufacturer, starting with the Wright brothers, has weighed their aircraft. Weighing the aircraft is a lift over drag (L/D) engineering aeronautic design function. The original Wright Flyer (Flyer I) weighed 604.1 pounds. A military version of the aircraft (Flyer III), capable of carrying one passenger, was procured by the Army Signal Branch for $30,000, thus establishing the first CER at $49.66 per pound.

The Story behind X-1

The X-1E is part of the Bell Aircraft X-1 series of aircraft that broke the sound barrier on October 14, 1947. It is the most photographed aircraft at NASA Armstrong, yet no one knew how much it cost to design, build, nor fly it?

I made a quick cost estimate using the Wright Flyer weight CER and adjusted for inflation. This gave me an estimate of $1.8 million in FY52 dollars, which is reasonably close to the actual cost.

Challenges in getting cost data

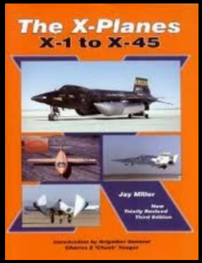
Timeline

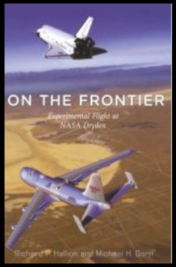
- 1940’s 50’s, 60’s & 70’s. . . Were basically joint-funded Programs; NACA, NASA and various Departments of Defense (DoD) programs.
- Salary Dollars were paid under a different “Appropriation”.
- NASA Dryden/Armstrong was under various NASA Centers until January 1994.
- Full Cost Accounting did not go into affect until 2002.
- Some Project Managers (PM) have volumes of cost data stored away in their cabinets.
  - Organized in 3-ring binders
  - Organized by burning; technical, scope, schedule, and cost data onto CDs

- NASA has a Cost Analysis Data Requirement (CADRe) for projects subject to NPR 7120.5E.
- In general, CAD and NASA Aeronautic Centers will cover CADRe for 7120.8 Research and Technology Program and Projects i.e. X-Planes.

Source of the Data

- NASA Technical Libraries
  - Armstrong's Technical Reference Library
  - Marshall Space Flight Center – Library "Redstar"
- Various publications "Books" specifically written on X-Planes
  - "The X-Planes"; written by Jay Miller
  - "On the Frontier"; written by Richard Hallion & Michael Gorn.





- Subject Matter Experts
  - Dr. Joseph Hamaker
  - 3rd Parties "Cost Research" Companies
- Government Accountability Office (GAO)
  - Various Cost Reports on X-Planes
- Industrial Partners or various Aeronautical Manufactures
  - Proprietary and "thin-slicing" the data
- Wikipedia and other "on-line" sources
  - Beware of the information and document the source, date, and URL

Hierarchal Cataloging of the data

- Some of the X-planes had three or mores sources of Cost Data.
  - For Example: NASA Technical Data, GAO, Hamaker; for the same plane
  - How does the Cost Engineer know who's data is correct?
- The entire set of X-Planes parameters are now catalog in an Excel data base with a word document linked in a separate folder serving as the source document.
- Source documents are in Word format.
  - **Name** of the person collecting the data
  - **Date** the source was collected
  - **URL** name if the source was collected on-line
    - Copy of the entire online source document includes references.
    - Note: a data element appeared to be changed within a 1 year time span.
- Hierarchy currently being used for Source Data.

1.) Government Source (Technical Libraries) go first-in-line.

2.) People associated in collecting Cost for NASA or for the Government.

3.) Thin-slicing, Wikipedia and other on-line forums.

Advance Composite Materials

- Advance Composite Materials (ACM) have gone a long way since the creation of carbon fiber and epoxy.
- Hand Lay-up versus Auto-Clave composite “Sandwich” Manufacturing
  - ➢ Hand-layup - is the process were resins are impregnated by hand in the form of woven, knitted, stitched or bonded fabrics. Hand-lay up process usually accomplished by rollers or brushes and cooked in a warm “unpressured oven”, cured under standard atmospheric conditions.
  - ➢ Autoclave - eliminates voids by placing the layup within a closed mold and applying vacuum, pressure, and heat.

- ACM aircraft manufactures are replacing 30,000 or more rivets and other components that were used by earlier aircraft manufacturing processes.

Cost of using Advance Composite Materials for prototyping X-Planes

- Large and small aircraft manufactures are using Advance Composite Materials.
  - Reports are coming in with a 30% cost saving from aircraft companies using Composites rather than Aluminum and Rivets.
  - Yes, there were known problems with adhering process in the past – which now seems to be fixed.

- Eliminate the need for “Unidentified Future Expenses (UFE).

Parametric Cost Modeling

- Assumptions
  - Cost can be predicted by a few design parameters
  - Cost is from initial concept to first flight
- Parameters
  - Technical and performance parameters for 22 experimental aircraft
    - Dry Weight, Takeoff Weight
    - Length, Wing Span, Wing Area
    - Mach, Thrust, Speed Regime
    - Maximum Altitude, Range
    - Material, Number of Engines, Crew size
- Goal
  - Identify the best parameters (predictors of cost)
  - Develop the best Cost Estimating Relationship (CER)

Linear Regression

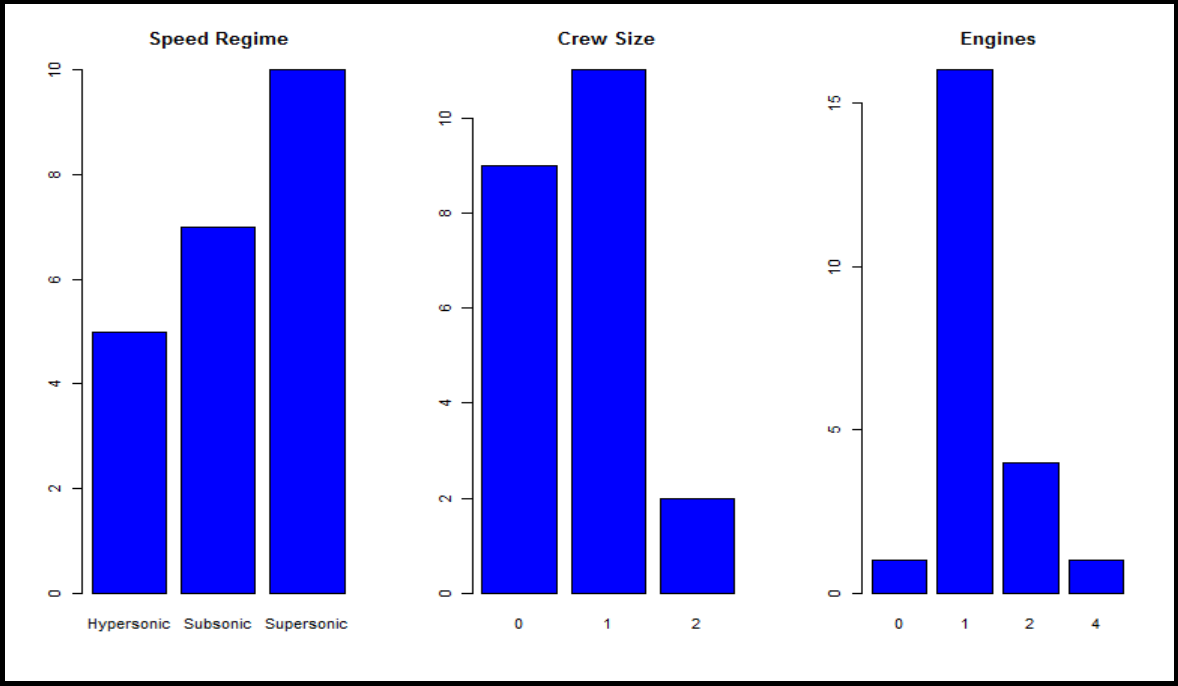
- Supervised learning
- Conceptually simple
- $Y_j = \beta_0 + \beta_1 X_{1j} + \beta_2 X_{2j} + \ \ldots + \beta_n X_{nj} + \varepsilon_j$
- Assumptions
  - Expected value of Y is a linear function of the X’s
  - Unexplained variations in Y are independent and normally distributed
  - All errors in Y measurements have the same variance

Summary of Parameters

Parameter	Mean	Median	Std Dev	Min	Max
Cost	357.97	107.80	489.77	12	1600
Dry.Wt	11,102.36	6800	9,222.96	377	28,814
Length	34.56	30.96	16.86	7.42	69.25
Height	11.26	10.83	4.39	3.13	23.75
TO.Wt	17,583.54	12,125	15,296.72	480	50,000
Range	1,784.05	240	5,307.26	1	25,000
Max.Speed	2,284.76	996.5	4,169.56	172.50	19,030
Mach	4.12	1.38	7.17	0.23	25
Max.Altitude	94,489.54	47,500	138,593.20	5,000	599,808
Thrust	18,385.14	10,240	19,559.06	0	60,000
Wing.Span	23.97	20.66	18.93	0.5	77.58
Wing.Area	207.10	161.00	160.65	0.5	590

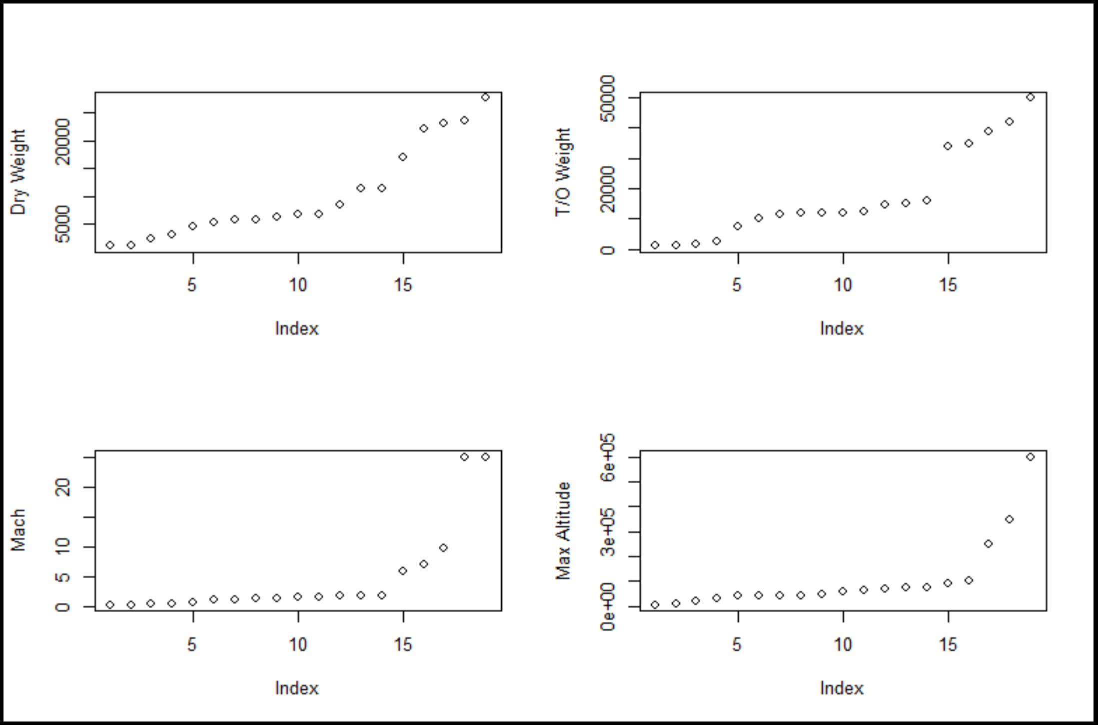
Narrowing Field of Predictors

- **Categorical Variables**
  - Data points in each category
    - Sufficient
    - Balanced

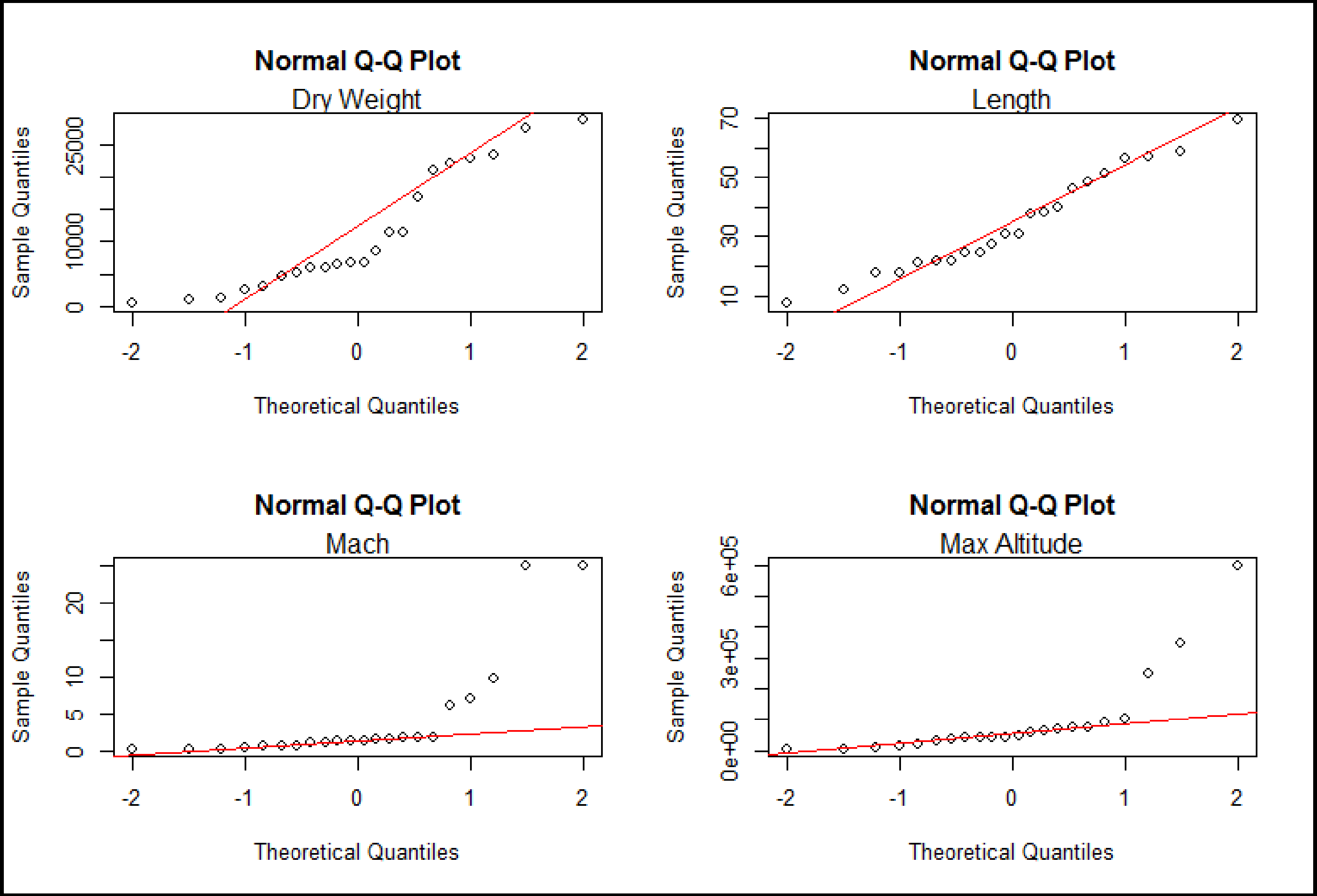


Narrowing Field of Predictors

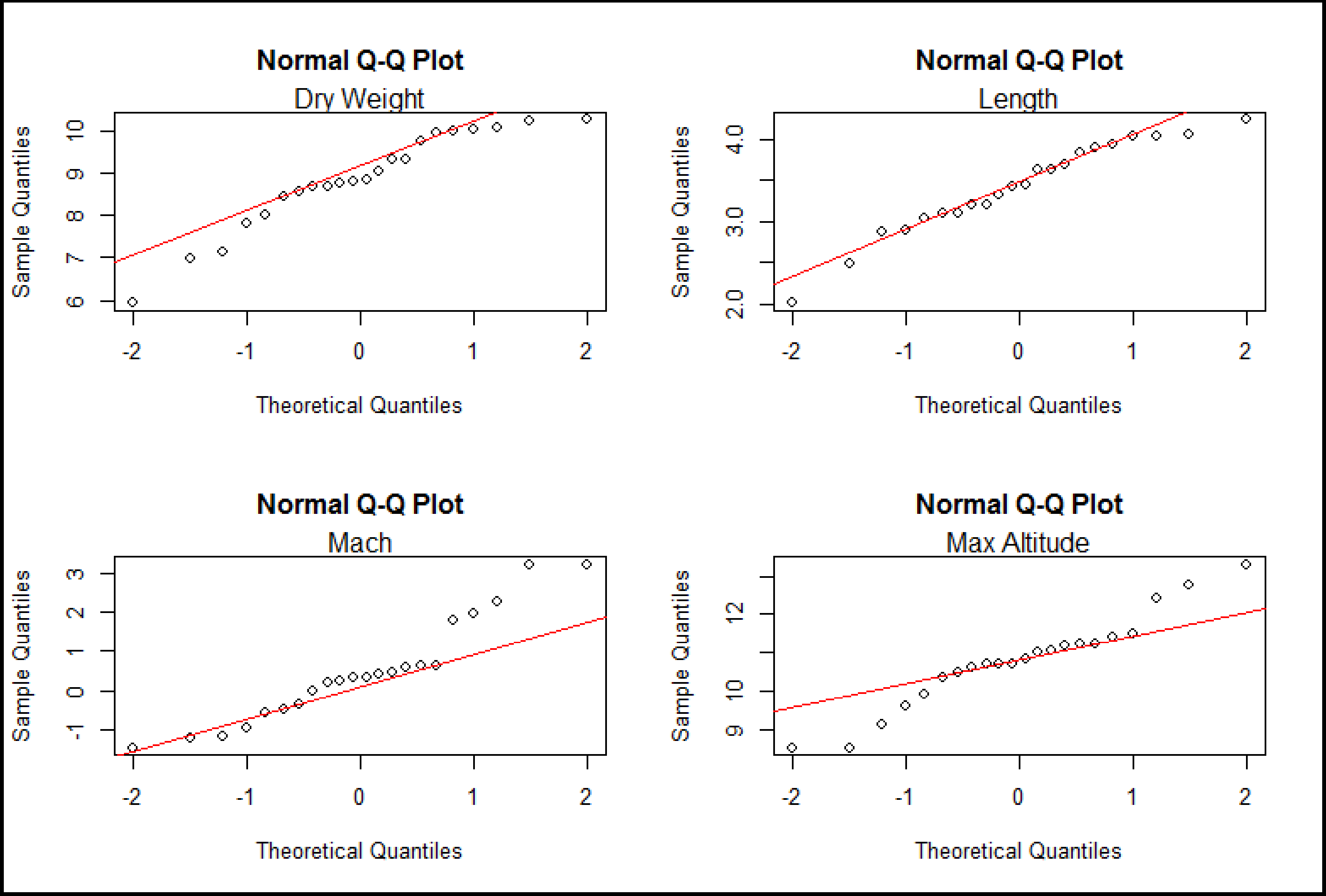
- **Continuous Variables**
  - Groupings
  - Outliers
  - Spread of Data Points



Distribution: Original Data

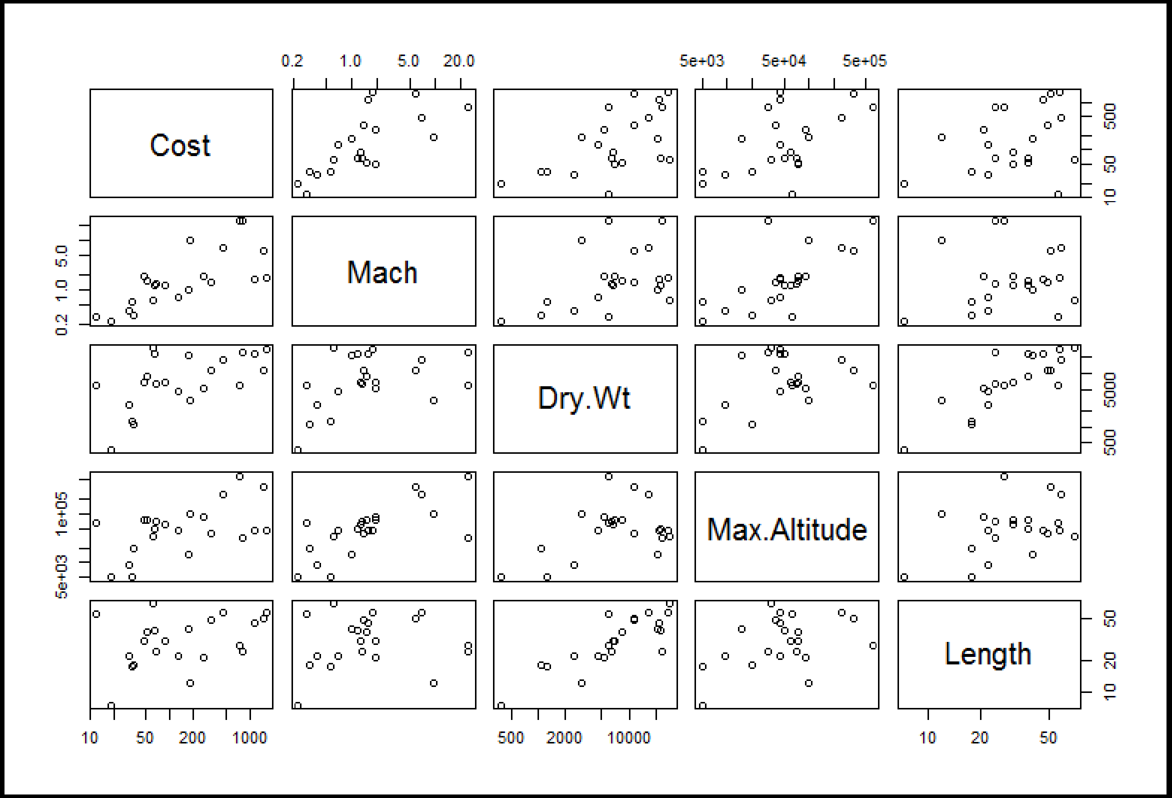


Distribution: Log-Transformed Data



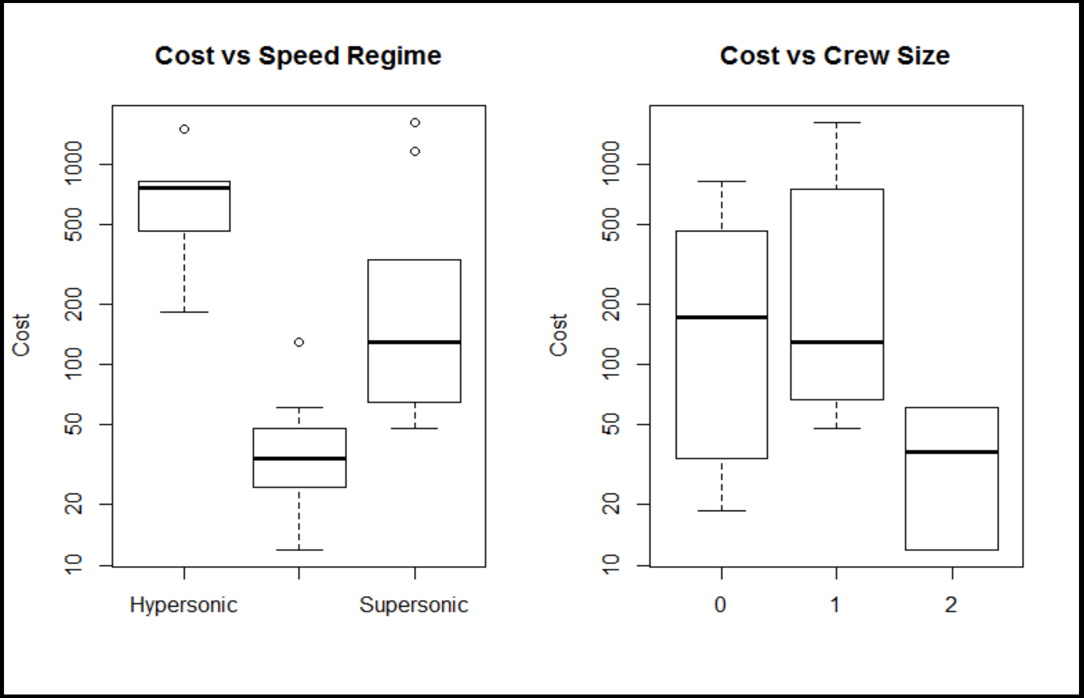
Identifying Best Predictors

- **Pairwise scatter plots**
  - Linear relationship to Cost
  - Correlation with other predictors

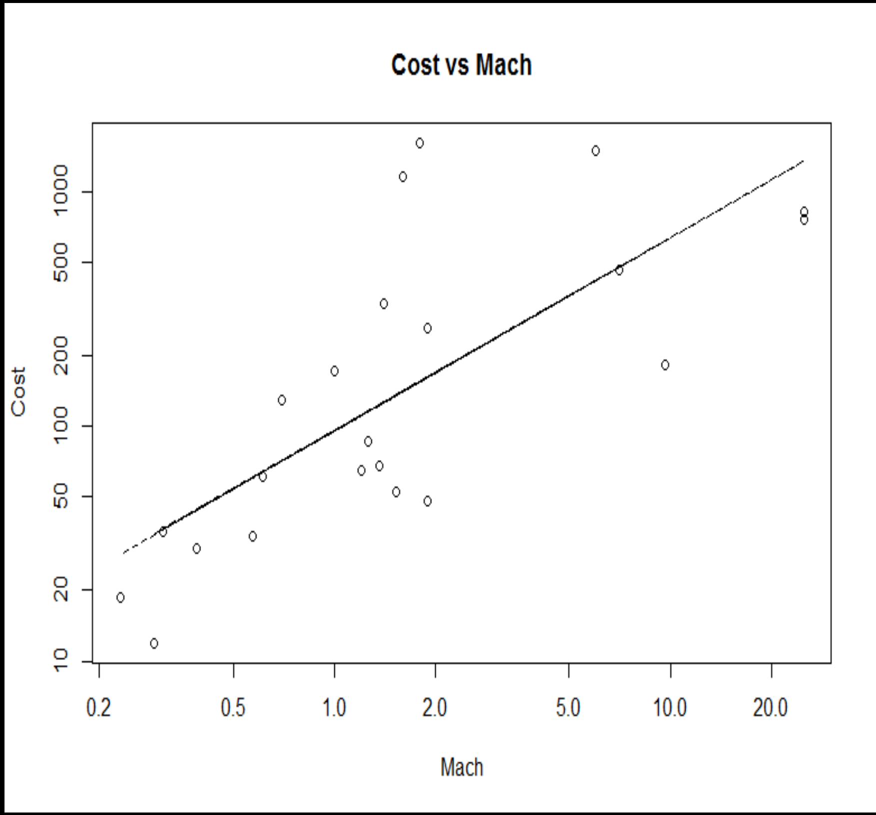


Identifying Best Predictors

- **Box plots**
  - Speed regime a clear cost predictor
    - Insufficient data in each regime
    - Highly correlated with Mach
  - Overlap in Crew Size data

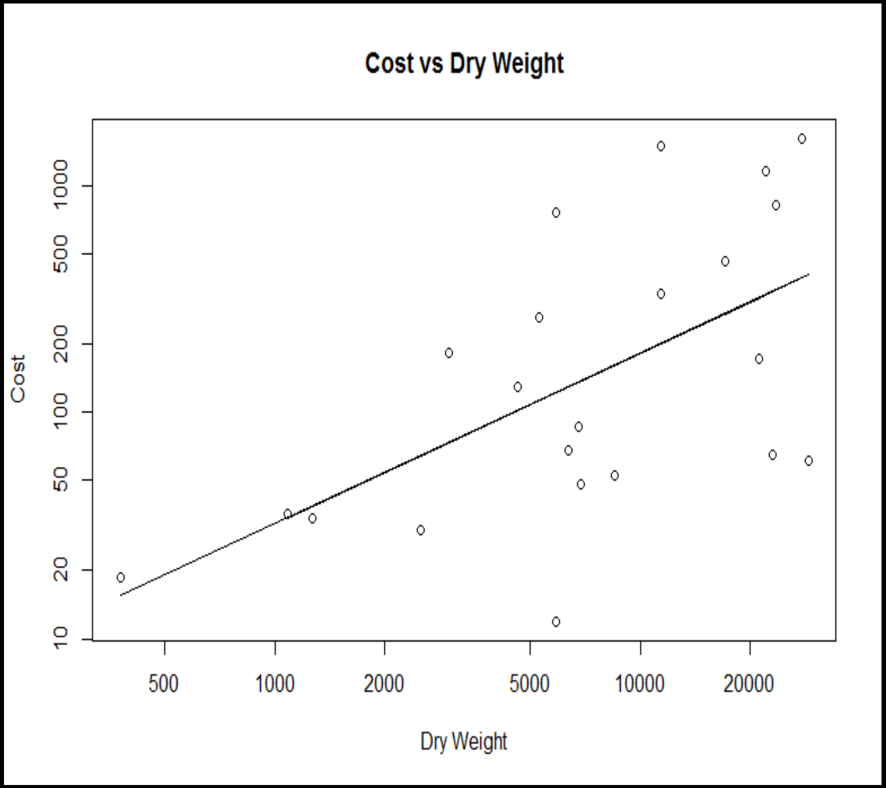


Cost vs Mach




```
Cost ~ Mach

Residuals:
    Min      1Q  Median      3Q     Max
-1.2106 -0.5649 -0.3293  0.5581  2.3363

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   4.5592     0.2276  20.034 1.05e-14 ***
Mach          0.8205     0.1659   4.946 7.79e-05 ***
---

Residual standard error: 1.007 on 20 degrees of freedom
Multiple R-squared:  0.5501,    Adjusted R-squared:  0.5276
F-statistic: 24.46 on 1 and 20 DF,  p-value: 7.79e-05
```

Cost vs Dry Weight




```
Cost ~ Dry.Wt

Residuals:
    Min      1Q  Median      3Q     Max
-2.3180 -0.7239  0.1129  0.8535  2.0023

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -1.7177     2.0576  -0.835  0.41369
Dry.Wt        0.7516     0.2307   3.258  0.00393 **
---

Residual standard error: 1.213 on 20 degrees of freedom
Multiple R-squared:  0.3468,    Adjusted R-squared:  0.3141
F-statistic: 10.62 on 1 and 20 DF,  p-value: 0.003934
```

Multiple Linear Regression

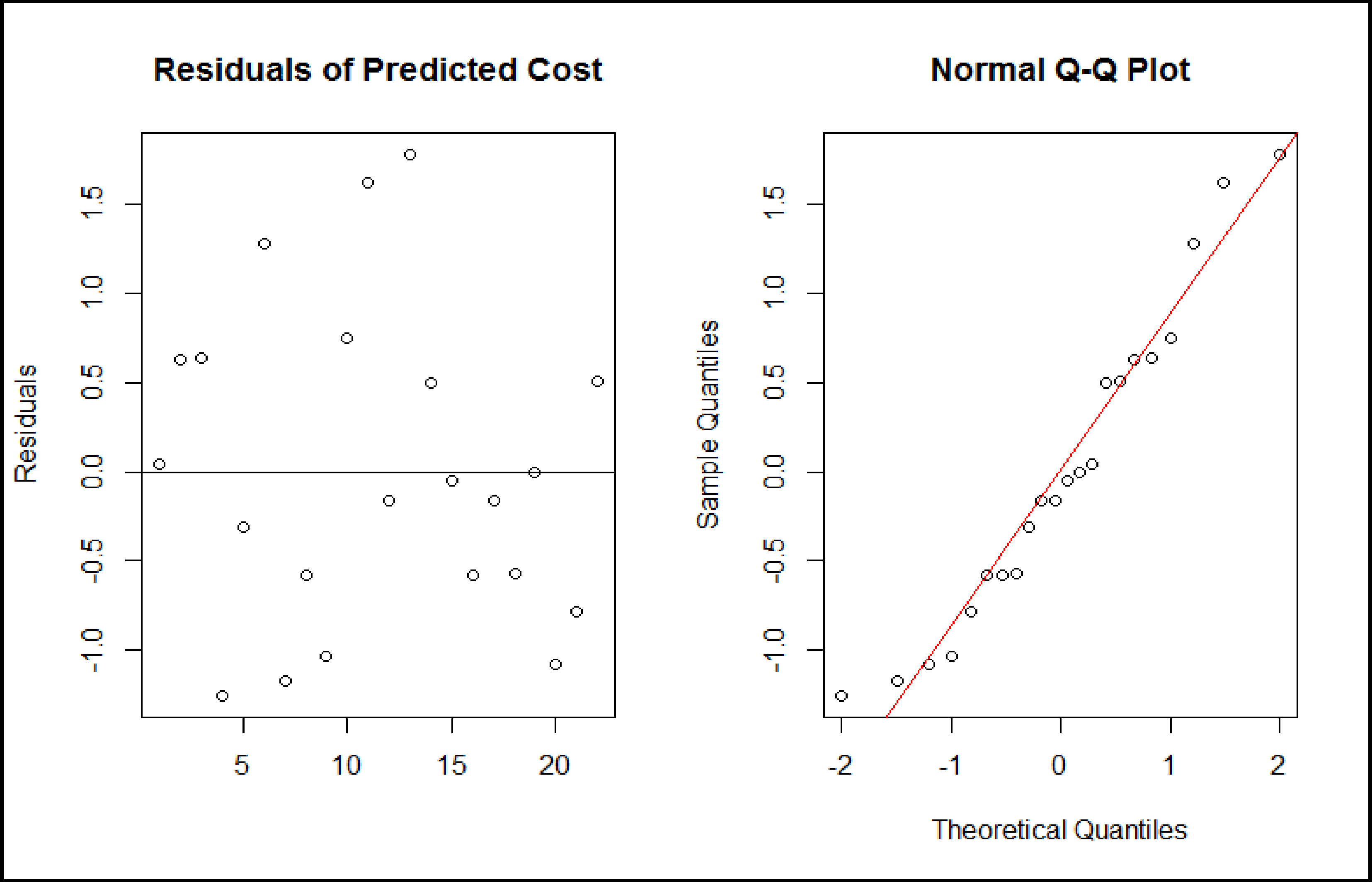
- Aircraft too complex for simple linear regression
  - Use more than one predictor in model
  - Limited by number of data points in database
    - Over fit data if too many predictors
    - Higher R^2 but lower predictive accuracy
- Variable selection
  - Start with best predictors identified with simple linear regression
  - Add predictors one at a time to identify best possible model
- Best Models
  - One predictor: Cost vs Mach
  - Two predictors: Cost vs Mach + Dry Weight
  - Three predictors: Cost vs Mach + Dry Weight + Max Altitude
- **Final Model: Cost vs Mach + Dry Weight**

Multiple Regression Model

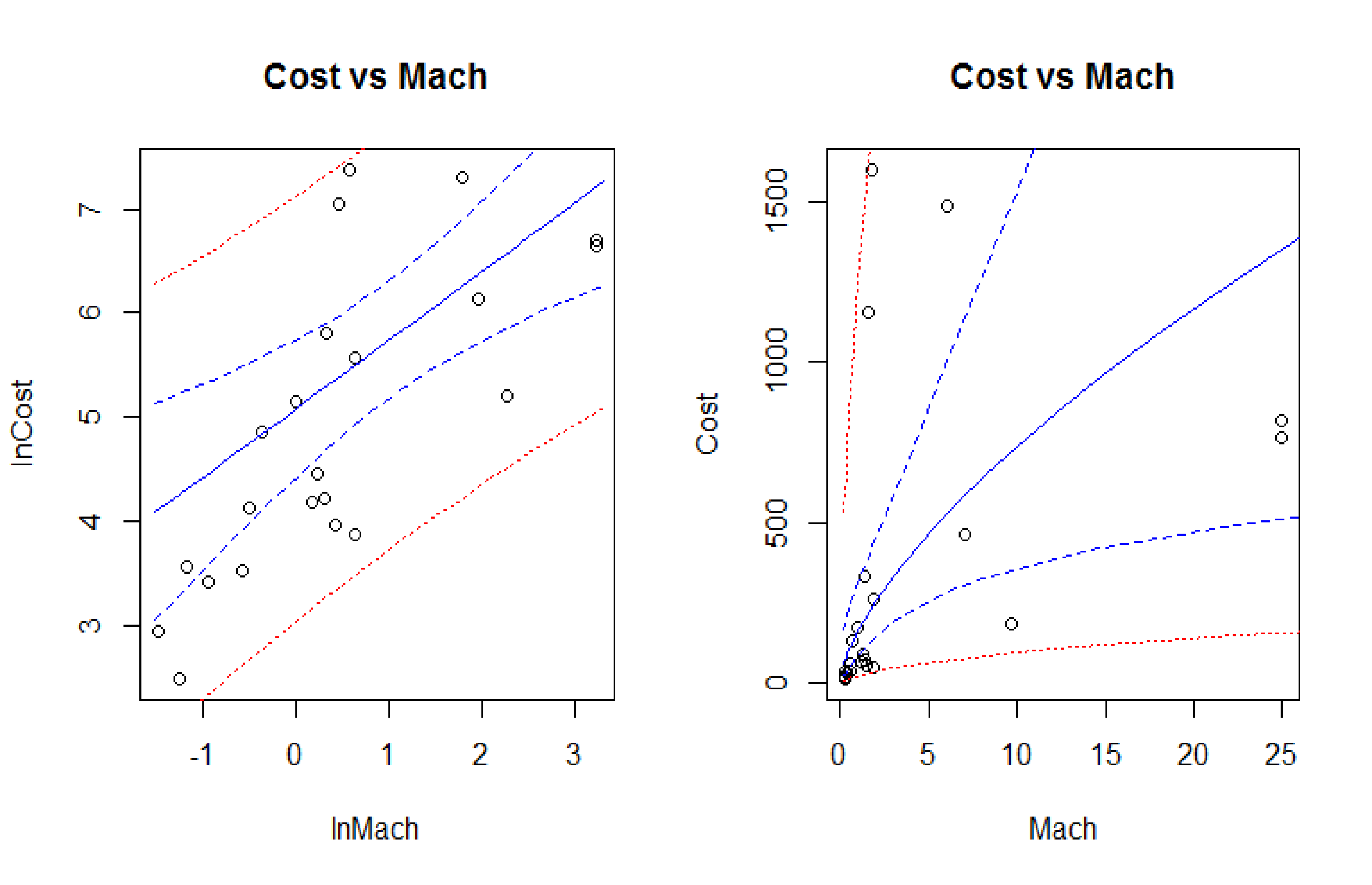
```
Cost ~ Mach + Dry.Wt

Residuals:
    Min      1Q  Median      3Q     Max
-1.2519 -0.5805 -0.1066  0.5989  1.7749

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.8883     1.7024   0.522 0.607842
Mach          0.6630     0.1687   3.930 0.000899 ***
Dry.Wt        0.4229     0.1946   2.173 0.042652 *
---

Residual standard error: 0.9243 on 19 degrees of freedom
Multiple R-squared:  0.6397,   Adjusted R-squared:  0.6017
F-statistic: 16.86 on 2 and 19 DF,  p-value: 6.146e-05
```

	Cost	Mach	Dry.Wt	Max.Alt	Length
Cost	1.00	0.74	0.59	0.54	0.36
Mach	0.74	1.00	0.43	0.70	0.12
Dry.Wt	0.59	0.43	1.00	0.43	0.83
Max.Al	0.54	0.70	0.43	1.00	0.42
Length	0.36	0.12	0.83	0.42	1.00

Model Assumptions

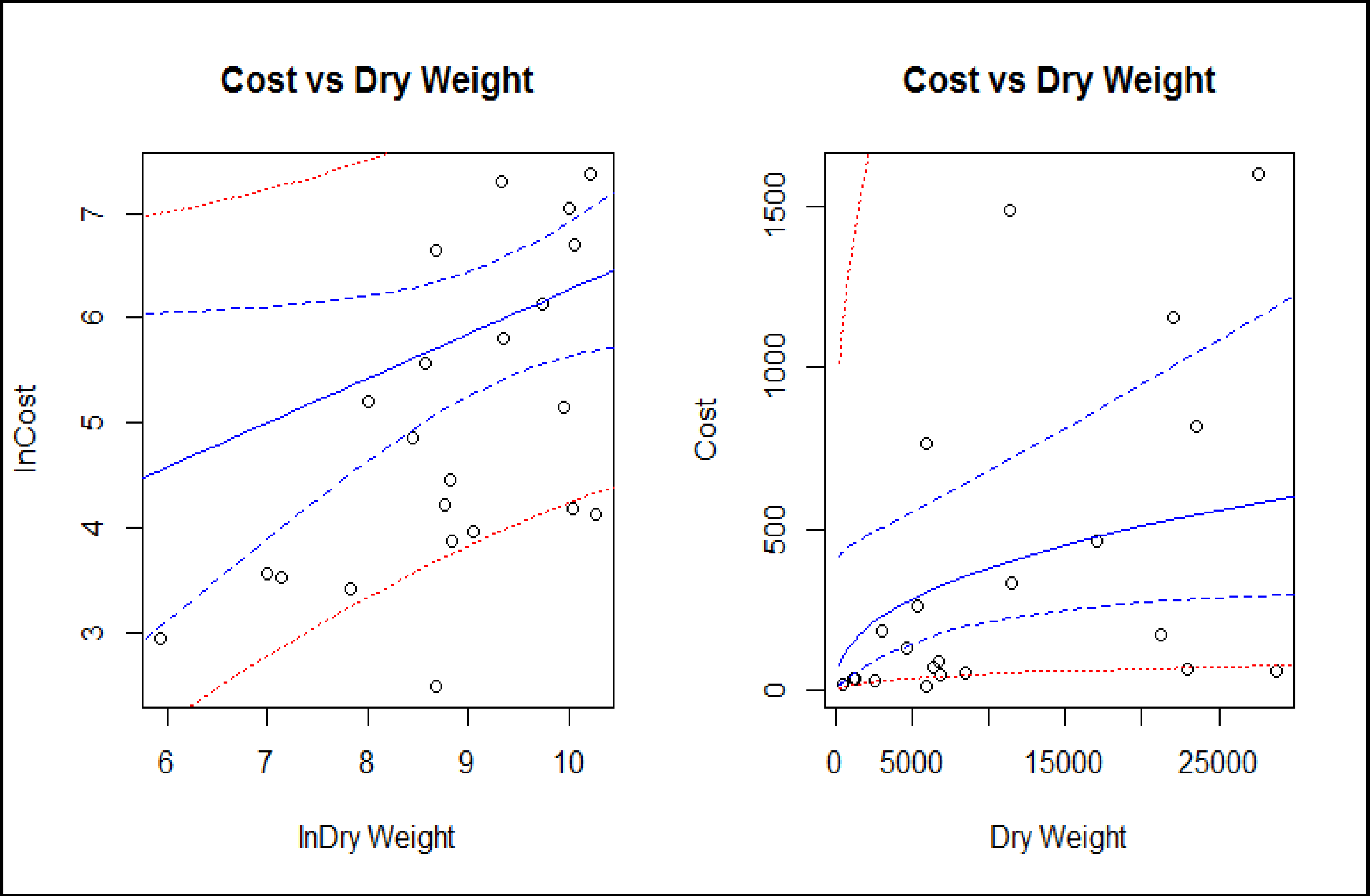


Final Model



Cost vs Mach
lnCost
3
4
5
6
7
-1
0
1
2
3
lnMach
Cost vs Mach
Cost
0
500
1000
1500
0
5
10
15
20
25
Mach

Final Model



Cost vs Dry Weight
lnCost
3
4
5
6
7
6
7
8
9
10
lnDry Weight
Cost vs Dry Weight
Cost
0
500
1000
1500
0
5000
15000
25000
Dry Weight

Cost Predictions ($millions)

Configuration	Point Estimate	Lower Estimate	Upper Estimate
HWB	173.14	86.69	345.81
ND8	159.89	76.22	335.41
TBW	164.52	82.12	329.57
LBFD	179.98	121.40	266.84
NGSF	320.00	210.00	352.00

Future State

- Tow Glider Assisted Launch System (TGALS) has currently been priced using the earlier algorithms of Armstrong's Parametric Cost Model.

2 Minute TGALS Video

Future X-Planes and X-Wings








Summary

- Within a two-month effort the Armstrong Cost Engineering Team has gone through the full process in developing a parametric cost model.
- We have identified and collected key parameters, such as; dry weight, length, wing span, manned vs unmanned, altitude, Mach and thrust.
- We have summarized the Variables.
- We created a regression analysis on 22 CERs of the 65 X-Planes that are currently in the data base.
- We have gone through the initial stages in determining the “best fit” for R2 values.
- We have parametrically priced out several future X-Planes.
- More work needs to be done !

Questions

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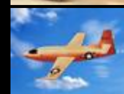
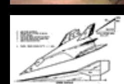
X-Planes in DB with Cost Data

1. WBF 
2. X-1 
3. X-1E 
4. X-15 
5. M2-F2 
6. HL-10 
7. X-24A 
8. X-24B 
9. X-24C 
10. X-32 
11. X-33 
12. X-34 
13. X-35 
14. X-36 
15. X-37B 
16. X-40A 
17. X-43A 
18. X-53 
19. X-55 
20. X-56A 
21. Proteus 
22. DC-X 

Example of X-Plane Data Base

Number	X-Plane Name	Photo	Manufacture	Year	Maiden Flt	Org Cost	Cost FY16$	Dry_Wt	Avg_Cost	Wt_Ma	Ma_Lnth	Alt_Thr	Length	Wing Span (ft)	Wing Area (sq ft)	Height (ft)	T/O Wt (lbs)	Crew	Range (nm)	Max Speed (mph)	Mach (ma)	#of Eng	Eng Model	Thrust (lbs)	Material	TF	Ceiling (ft)
0	Flyer 1		Wright Bro	1909	12/17/03	0.030	2.8	605	3.5	2.3	3.1	5.2	21	40	510	9.00	745	1	0.0	30	0.02	1	Stra-4 V	170	Cloth & Wood	4	30
1	X-1 (Sterk		Bell Aircraf	1945	01/25/46	6.6	59.8	6,750	90.3	85.4	84.3	101.3	31	28	130	10.83	12,250	1	80	957	1.26	1	XLR11	6,000	Aluminum	151	60,000
2	X-1 (Hama		Bell Aircraf	1946	04/11/47	6.6	86.7	7,000	102.9	97.1	96.1	115.4	31	28	130	10.00	12,225	1	80	1142	1.50	1	XLR11	6,000	Aluminum	151	70,224
3	X-1 #3		Bell Aircraf	1951	07/24/51		23.5	6,850	116.4	112.5	114.6	122.1	31	23	115	10.83	14,750	1	305	1450	1.90	1	XLR11	6,000	Aluminum	54	75,000
4	X-1E		Bell Aircraf	1952	12/12/55	0.5	48.3	6,850	116.4	112.5	114.6	122.1	31	23	115	10.83	14,750	1	305	1450	1.90	1	XLR11	6,000	Aluminum	26	75,000
5	X-2		Bell Aircraf	1952	06/27/52			12,375	188.1	178.4	173.2	212.6	38	32	260	11.75	24,910	1	190	2094	2.75	1	XLR25	15,000	Aluminum	20	126,000
6	X-3		Douglas Ai	1952	10/20/52			16,120	89.7	91.9	109.0	68.2	67	23	166	12.50	23,840	1	500	650	0.85	2	J34-WE	6,740	Titanium	54	35,000
7	X-4		Northrop	1948	12/15/48			5,507	57.4	59.4	49.9	63.1	23	27	300	14.75	7,780	1		616	0.81						42,000
8	XQ-5		Lockheed T	1951	04/01/51			7,937	268.0	202.2	240.9	360.8	38	10	60	6.92	8,000	0	113	3273	4.30	3	XM-45	100,000	Steel, Aluminum		98,000
9	X-5		Bell Aircraf	1951	06/20/51			6,350	67.5	68.4	71.0	63.1	33	27	175	12.00	9,875	1		705	0.93						42,000
10	X-6		Convair (Nev	1954	N/A	4.1		166,165	120.9	157.5	139.8	65.3	162	**230**	4772	46.67	410,000	13	10000	390	0.51	10			Aluminum		43,600
11	X-7A		Lockheed (	1951				2,636	167.6	133.9	217.0	151.9	33	12	52.3	7.00	8,108	0		3273	4.30	1			Steel & Nickel Alloy		106,000
12	X-7B		Lockheed (	1960				3,345	175.3	146.6	227.4	151.9	35	10	60	7.44	8,350	0	134	3281	4.31	1			Steel & Nickel Alloy		106,000
13	X-8		Aerojet	1952	02/12/49			135	456.7	50.4	178.6	1141.1	20	5	36	1.25	1,097	0	20	4020	5.28	2	RTV-N1(	12,000	Steel & Nickel	68	800,000
14	X-9		Bell Aircraf	1949	04/28/49			2,125	90.7	75.0	95.5	101.6	23	8	70	1.00	3,495	0	50	1522	2.00	1	XLR65	3,000		31	65,000
15	X-10		North Ame	1953	10/13/53			25,792	171.6	193.8	206.2	114.9	66	28	525	14.75	42,000	0	850	1560	2.05	2	XJ40-W	21,800		27	44,800
16	X-11		Convair (At	1957	06/11/57			12,490	444.2	431.4	896.4	4.8	96	0	0		80,000	0	600	8067	10.60					8	
17	X-12		Convair (At	1958	19/7/1958			18,333	699.4	703.2	1390.0	4.8	103	0	0		240,000	1	6000	13698	18.00						
18	X-13		X-15			3	55		22		13K	$91M		NAA	13 (#1)	[illegible].17	7,313	1	167	483	0.63						
19	X-14		Bell Aircraf	1957	02/19/57			3,173	24.9	21.0	21.1	32.6	26	34	179	8.83	4,269	1	300	172	0.23						20,000
20	X-15 (Tec		North Ame	1959	06/08/59	1309.9		11,374	410.1	267.5	343.8	619.0	50	22	200	13.50	33,000	1	280	4091	5.37	1	XLR99	56,100	Steel, Titaniun	199	353,760
21	X-15		North Ame	1959	06/08/59	1318.9		11,374	426.4	286.1	369.9	623.2	50	22	200	13.50	31,275	1	275	4534	5.96	1	XLR99	57,850	Steel, Titaniun	199	354,000
22	X-15 (Har		North Ame	1959	06/08/59	1318.9	1485.6	11,374	427.1	287.4	378.0	615.9	51	22	200	13.50	34,000	1	280	4567	6.00	1	XLR99	57,000	Steel, Titaniun	199	350,064